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Collection and storage of solar gains incident on the floor in a house during the heating season

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Abstract

Large amounts of south facing windows can help reduce heating demand in the winter and shoulder seasons by allowing high levels of solar radiation to enter the building. One problem that may arise from large areas of south facing glazing is overheating of the adjacent rooms, even during winter in a cold climate.

Cooling of the floors may provide a means to prevent overheating in such a situation. Cooling a floor prevents solar gains absorbed by the floor from being transferred to the space by convection or infrared radiation. This cooling can be achieved with the use of water pipes in the floor. The heat removed can be upgraded to a higher temperature with a heat pump, and then may be stored in a thermal storage tank for space heating and domestic hot water heating.

This paper shows preliminary simulation results of such a system for a house in Ottawa, Canada. The house contains a much larger south facing window area than is typical. In periods of overheating, the solar gains are absorbed by the floor cover and collected by the cold pipes in the floor. The heat is upgraded by a heat pump and stored in a hot storage tank.

Preliminary modelling results show that, with the use of a large thermal storage tank (2 m^3), space heating and domestic hot water demand with this type of system may be reduced by as much as 24%, when compared with a more conventional house.

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Keywords: radiant floor, heat pump, building simulation

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1. Introduction

In 2011, space heating of residential, commercial, and institutional buildings accounted for 16% of the total energy use in Canada. Space heating also accounted for 62% of the energy demand of residential buildings [1]. In order to improve energy efficiency in residential buildings such as houses, space heating demands must be lowered.

In highly insulated and air tight houses, the heating demands are usually much lower than conventional houses [2]. Passive measures such as using south facing windows for solar gains during the heating season can be used to further lower the heating demand. Sander and Barakat [3] have shown that for a highly insulated house, the optimal south facing glazing area for reducing heating demand is approximately 4.8% of floor area for triple pane, and 3.4% for double pane windows. More recently, Proskiw has shown that increasing the thermal mass in a Canadian house may yield 2-7% heating demand reduction, but that the cost involved is often prohibitive [2]. Proskiw also presents a maximum south-facing glazing area of 6% of floor surface area, after which additional glazing area can result in overheating of the space [2].

1.1. Problem

Although increasing south facing window area beyond the optimal point described previously will allow for more gains in the house, these gains will not be useful [4, 5]. In single detached family house, one issue that may arise from highly glazed south facades and tight envelopes is overheating, even in winter. Additionally, a mismatch of solar gains availability (day) and peak heating loads (night) means that heating will be required at night even for highly insulated houses.

1.2. Proposed solution

With the use of a radiant floor system, it is possible to collect those solar gains incident on the floor in zones with a large amount of south facing windows. Embedded pipes in the floor can be used to cool the floor and carry the heat away from the floor. A water-water heat pump can be used to supply cold water to the floor and hot water to a storage tank. In periods of heating demand, the stored hot water is sent back to the floor to heat the space. Additionally, the hot water storage tank can be used to heat domestic hot water. Figure 1 shows a schematic of such system with cooling and heating of two zones.

2. Models

In order to evaluate the system as shown in Figure 1, a model was developed using the TRNSYS/ESP-r co-simulator [6]. The building envelope and radiant floors were modeled in ESP-r, while the rest of the mechanical system was modeled in TRNSYS. Additionally, a typical house model was developed in order to compare a conventional HVAC system with the solar collection system. All simulations were run with a 3 minute time-step for an entire year with an Ottawa, Canada CWEC climate file [7].

2.1. Building model

A single-family detached home was modeled in ESP-r. The model was based on the newly constructed Urbandale Centre for Home Energy Research on the Carleton University campus in Ottawa, Canada. All modelled glazing was triple pane with two low-e coatings, and argon filled. The center of glass nominal U-value was 0.9 W/m^2K and the nominal SHGC was 0.6. The exterior walls were timbre construction with 140 mm batt insulation in the cavity and 38 mm of continuous insulation. The exterior walls nominal R-value was approximately 4.2m^2K/W (U = 0.238W/m^2K). The house model consisted of an unconditioned basement, and two conditioned floors. The dimensions of the house were 12 m by 6 m. Two south facing glazing areas were modelled: 20.7 m^2 (14.4% south-facing glazing to floor area ratio) and 6.9 m^2 (4.8% south-facing glazing to floor area ratio).

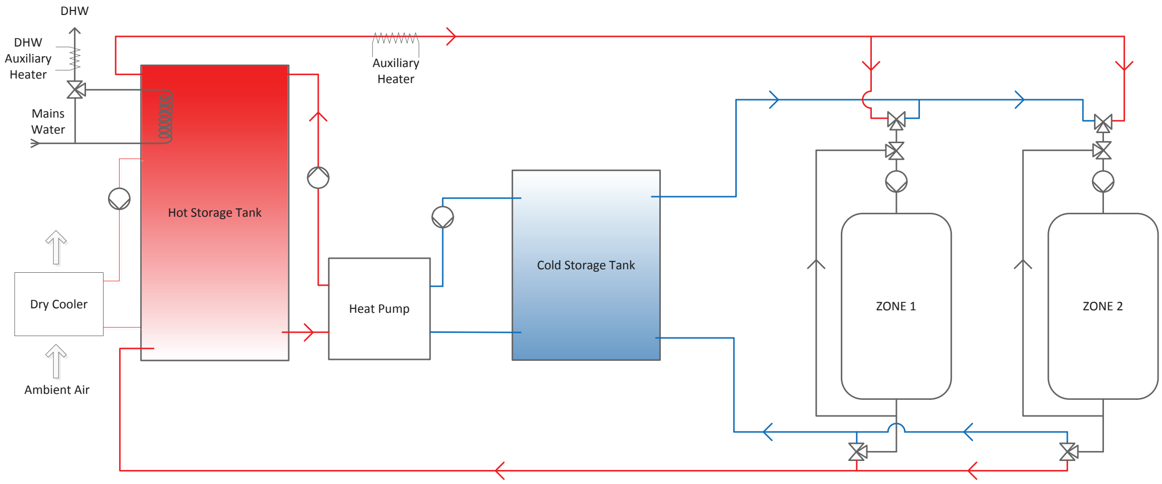

Figure 1 Schematic of mechanical system for solar collection with radiant floors and storage

The Alberta Infiltration Model [8] was used to calculate the infiltration based on the *energy tight* setting in ESP-r. This setting assumes a blower door test of 1.5 ACH at 50 Pa. A heat recovery ventilator with sensible and latent effectiveness of 0.6 and 0.7 respectively provided 198 kg/hour of fresh air to the house and was modelled in TRNSYS.

Due to the generally open concept of the first floor of the house, it was modelled as a single zone. There were four parallel radiant floor loops on the first floor. The second floor consists of three bedrooms and a hallway. Each of the bedrooms and the hallway were modelled as separate zones. Each of the second floor zones contains a single parallel radiant floor loop. The construction of the floors is shown in Table 1. The first floor was tiled, while the second floor rooms and hallway had a hardwood cover.

The radiant floors were the tube-in-subfloor type. This type of radiant floor consists of a grooved subfloor or rigid insulation layer and a conductive fin layer. The tubes lie in the grooves, while the fin enhances heat conduction to the floor cover. Figure 2 shows a section of a tube-in-subfloor system with grooves in the subfloor layer. These types of radiant floors have a lower thermal mass than embedded tube systems, which are typically made of concrete or gypsum cement. Additionally, the thermal resistance between the pipes and the space is lower in tube-in-subfloor systems compared with embedded tube systems. A model described by Brideau and Beausoleil-Morrison was used to simulate the tube-in-subfloor radiant floor system. [9]

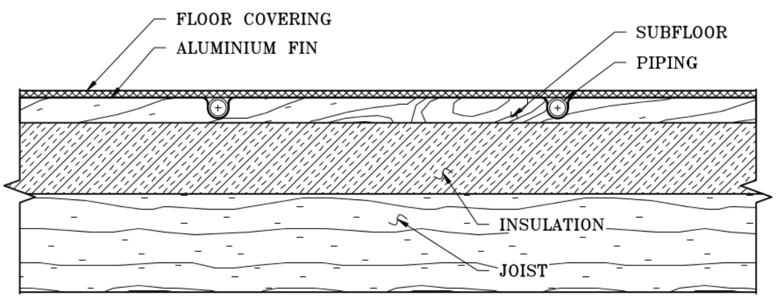

Figure 2 Tube-in-subfloor system

Casement windows were modelled to open when indoor temperature was above 25°C provided that the outdoor air temperature was at least 11°C and 1°C lower than the indoor temperature. Windows were shut when the indoor air temperature reached 21°C. This was to allow for some natural ventilation in the summer and shoulder seasons. Additionally, between May 1st and September 30th, indoor roller blinds were pulled down if the direct normal solar radiation intensity reached 400W/m^2, and pulled back up once it reached 200W/m^2. This was to prevent overheating during sunny summer days.

Non-HVAC electrical gains were taken from measured data by Saldanha and Beausoleil-Morrison [10] (house H12) and by Johnson [11] (house H14). The average annual non-HVAC electrical load of the 23 houses studied in both studies was 19 GJ. Both electrical gains profiles were used to evaluate the effects of the electrical gains on the proposed solar collection system. H12 had a total non-HVAC annual load of 39.5 GJ, whereas H14 had a total non-HVAC annual load of 15.5 GJ.

The kitchen related internal gains (stove and dishwasher) and 50% of all other non-HVAC internal gains were applied to the first floor. The clothes dryer internal gains were applied to the basement. Sensible load fractions as defined by Hendron and Engebrecht [12] were used for the stove, dishwasher, and clothes dryer. Additionally, outdoor air ventilation was applied to the space at a rate of 0.056 kg/s for each of the stove (for range hood operation) and the clothes dryer when in use. The remainders of the non-HVAC internal gains were divided equally between the other zones, including the basement. Internal gains for four occupants were added to the space, and assumed no occupants were present during week days between 8:00 and 17:00.

Table 1 Floor Construction

Layer	Specific heat (J/kg K)	Density (kg/m^3)	Conductivity (W/m K)	Thickness (m)
Insulation	960	100	0.036	0.0760
Subfloor	1880	450	0.1	0.0279
Fin	900	2700	234	0.0006
Hardwood[a]	1210	600	0.14	0.0191
Thinset mortar[b]	780	1860	0.72	0.0032
Backer board[b]	840	1461	0.277	0.0064
Thinset mortar[b]	780	1860	0.72	0.0032
Tile[b]	837	2100	1.1	0.0127

a - Hardwood cover
b - Tile cover

2.2. Plant model – solar collection system

The plant was modelled in TRNSYS. Figure 1 shows a schematic of the plant system. Zone 1 and 2 are the first and second floor respectively. The radiant floor supply temperatures were controlled with a floor surface temperature reset controller. A simple thermostat with a dead band of 2°C was used to turn the pumps on and off. The air temperature set points for cooling were 25°C between May 1st and September 30th, and 22°C the rest of the year. The heating set point was 20°C for the entire year.

The performance of a custom water-water heat pump was tested experimentally for various flow rates, and inlet temperatures at steady-state. Additionally, transient tests were performed. An empirical model was developed based on the results of those tests. This model was used in the TRNSYS plant simulations.

The storage tanks were modeled using Type 534 [13]. The cold tank had a volume of 0.454 m^3 and three hot water tank volumes were investigated: 3 m^3, 2 m^3, and 1 m^3. Water was drawn from the tanks to supply both sides of the heat pump. Similarly, water was drawn directly from the tanks to heat and cool the house. In heating mode, if the supply temperature required by the controller was not met by the hot tank, an auxiliary electrical heater was used to bring the water to temperature. The heat pump had a maximum condenser water temperature average temperature of 60°C above which it would shut off. A dry cooler was used to cool down the hot water tank if required. The maximum temperature at the bottom of the hot tank was set to 55°C during the heating season, whereas it was set to 45°C in the cooling season. The higher set point in the heating season was to allow for more heat storage, while the lower set point in the cooling season was to increase the coefficient of performance (COP) of the heatpump.

During periods of domestic hot water demand, a heat exchanger in the hot tank heats the incoming mains water to 45°C. If this temperature was not achieved due to low tank temperature, an auxiliary electrical heater was used to bring the water to temperature. Type 1243a [13] was used to provide a domestic hot water draw schedule based on ASHRAE 90.2. A total of 190 L/day was used in the model.

2.3. Plant model – typical house

The plant was modelled in TRNSYS. A gas furnace with a heating capacity of 6kW and 92% efficiency was modelled. An air conditioning unit was modelled with TRNSYS Type 921 [13], using manufacturer's data for a ducted air conditioning unit. The domestic hot water tank was modelled with TRNSYS Type 534. The tank volume was 0.454 m^3, and the heat loss coefficient was set to 0.34 $W/(m^2K)$. A gas heater with an efficiency of 90% provided heat to the tank, which had a setpoint temperature of 55°C.

3. Results

The 6.9 m^2 south-facing glazing case was simulated along with a typical HVAC system, as described in Section 2.3, to represent a more typical house. The 20.7 m^2 south-facing glazing case was modelled along the solar collection system described in Sections 1.2 and 2.2. The purpose of the large amount of glazing in this case was to allow as much solar gains as possible in the space for use by the solar collection system. If this much glazing were to be used with a conventional HVAC system, overheating would occur on sunny days, even during the coldest days of the year. For this reason, only the 6.9 m^2 glazing case was paired with the typical HVAC case.

Figure 3 shows annual results for the low electrical gains profile (house H14) on the left and high electrical gains profile (house H12) on the right. End-uses are reported for each category. For example, "Air Conditioning" represents the electricity use for the conventional air conditioner, expressed in GJ, and "Furnace" represents the natural gas consumption, expressed in GJ, using the Higher Heating Value.

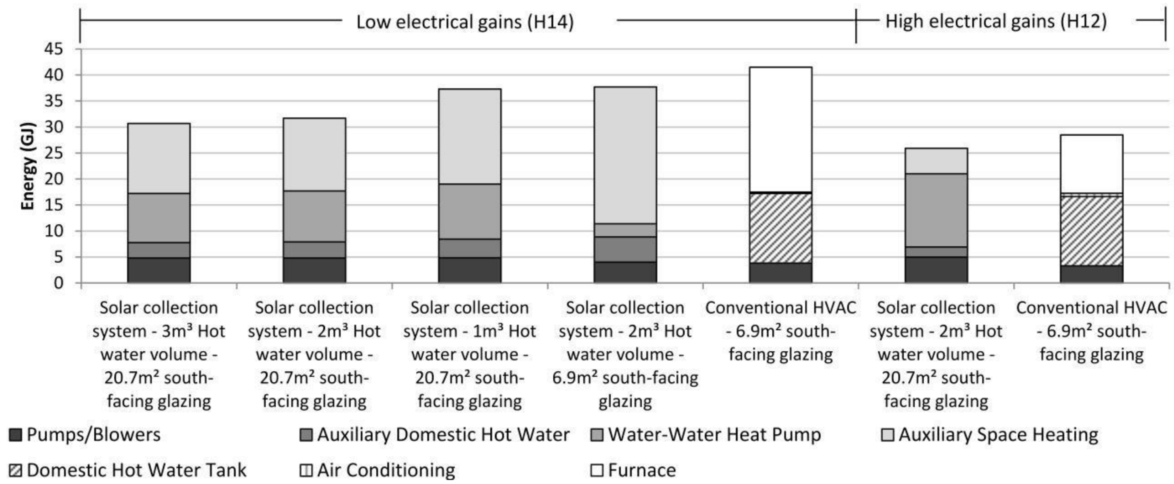

Figure 3 Results – Total annual end-use energy demand for HVAC and domestic hot water

Figure 3 shows that the solar collection system required less energy with a larger hot water storage tank, but the improvements decreased significantly with a tank greater than 2m^3. Also, the high glazing cases used less energy than the typical glazing case. Compared with the conventional house HVAC and glazing coverage (6.9 m^2 south-facing glazing), the solar collection system with 2m^3 hot water storage tank and higher glazing coverage (20.7 m^2 south-facing glazing) required 24% less energy annually. It is important to note that the solar collection system as modelled here was an entirely electrical system, while the typical HVAC system uses primarily natural gas. The solar collection system could be made to use natural gas as well for auxiliary DHW heating and space heating. If this was done and 92% efficiency was applied to the auxiliary heaters, the solar collection system would use 20% less energy than the typical HVAC and glazing coverage.

The high electrical gains reduced the heating requirements of the conventional HVAC (with 6.9 m^2 south-facing glazing coverage) by 53% compared with the low electrical gains profile (house H14). This lower heating demand caused the solar collection system to be less effective at reducing the total energy consumption when compared with the conventional HVAC system (with 6.9 m^2 south-facing glazing coverage). There was a 9% decrease in total energy consumption from the conventional HVAC and lower glazing coverage case to the higher glazing coverage solar collection system with the 2 m^3 hot water storage tank.

These results show that it is possible to decrease the energy demand of houses with the solar collection system, but that many factors can influence its performance. South facing glazing area, internal gains, and hot water tank size all have a significant influence on the reduction in energy demand with respect to a typical HVAC system.

4. Conclusion

In this paper, a new concept of a solar gains collection system with radiant floors is described and assessed with the use of a detailed building energy simulation model. It is possible to reduce energy consumption in houses using this system, but many factors have the potential to influence its performance. Three parameters were explored here: the hot water storage tank volume, the south facing glazing to floor area ratio, and the electrical internal gains in the space. All of these parameters were shown to have a significant effect on the annual energy consumption of the system.

These preliminary simulation results showed that the solar collection system may reduce the HVAC and domestic hot water energy demand by as much as 29% when compared to a conventional HVAC system in a house with more typical window area.

Future work will include an investigation of the effects of other parameters on the performance of the system, such as the heat dump setpoints in the hot water tank, night time setback, removal of internal roller blinds, and radiant floor supply temperature controls. Furthermore, the thermal comfort of the occupants will be assessed and the radiant floor model will be verified experimentally.

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